Actes des journées coton du Cirad-ca

Montpellier, du 20 au 24 juillet 1998

Programme Coton
Cirad-ca
Juillet 1998

COTONS, A COTTON SIMULATION MODEL FOR THE NEXT CENTURY

E. JALLAS[1,2], R. SEQUEIRA[3], P. MARTIN[2], S. TURNER[1] and M. CRETENET[2]
[1] USDA-ARS-CSRU, P.O. Box 5367, Mississippi State, MS 39762, USA. [2] Programme Coton, CIRAD-CA, BP 5035, 34032 Montpellier Cedex 1, France. [3] USDA-APHIS-CPHST, 1509 Varsity Drive, Raleigh, NC 27606, U.S.A.

Abstract: Traditional plant architectural models or 'visualization models' propose to visually create realistic three-dimensional plants. The visualization is based on field sampling and the application of an algorithm to standardize the three-dimensional description of a plant. "L-systems" and the "Reference Axis" are two such approaches. Mechanistic or physiologically based models, built using mathematical expressions of the interactions between plant components propose to describe how a plant functions. They simulate physiologically realistic plants based on estimates of physiological development and growth. Their equations are derived from field experiments. In this study we integrated both modeling paradigms. We used functions and concepts obtained from mechanistic and architectural modeling theories and developed an integrated system. The system was derived from an enhanced 'mechanistic' model, GOSSYM, with 3D architectural extensions. We accomplished this by associating growth and development functions with actual locations in three-dimensional space. The resulting model allows vastly improved model output interpretation, use of the model as a surrogate experimental environment and to better integrate our knowledge about how plants grow into a unique system. The new model, named COTONS, produces "life-like" plants. Now the farmer deals with simulation results analogous to the ones he deals with in a 3-dimensional world. Very importantly, variability is captured and expressed visually. This is the first step for better characterizing production risk in human-based terms. This new model symbolizes crop models for the next century.

Introduction. Worldwide cotton represents about 50% of the fiber used in the world, it is the fifth row-crop and in some countries it is the first agricultural resource.

Cotton is also a complex plant. It is a perennial plant with an indeterminate habit, but it is cultivated as an annual crop. It develops monopodial structures at the same time as sympodial structures, and it regulates its carrying capacity through fruit abscission. The main stem and the vegetative branches are monopodial structures, which means that all internodes are produced by the terminal apex. Fruiting branches are sympodial structures. This implies that each internode is produce by an axillary bud which will be transformed into a fruiting site. Each internode bears a leaf and two axillary buds; thus a cotton 'tree' increases its photosynthesis potential by increasing the size of its light captors and by increasing their number through morphogenesis-by adding nodes. Fruiting sites can be abscised in response to nutritional stresses. These characteristics are important because there is always competition between vegetative development and reproduction on a cotton plant. Figure 1 shows the different growing phases of the cotton crop. During the *green* phase, the plant installs its "photosynthetic potential". There is a slight "competition" between vegetative growth and fruit production. Fruit demand stays low but some squares could be abscised if the carbohydrate supply is limited. During the *red* phase, after first boom, the fruit demand increases dramatically. Boll growth demand increases exponentially and competition between vegetative growth and reproduction become determinant for further plant development. Fruit demand is served as a priority and when carbohydrate production becomes insufficient the plant stops its vegetative growth. It reaches 'cut-out' stage (no further vegetative growth in favor of reproductive development) and numerous fruit are abscised in response to carbohydrate stress. The last period is the maturation period shown in the figure in gray. The number of bolls per plant at harvest will depend on events which occurred long before boll setting. Square and boll abscission determine this number but they are dependent on crop development and growth which are under the control of the dynamic states of environment. Thus the period where there is interaction and competition between growth and development is relatively important.

The COTONS model. COTONS is based on the GOSSYM model. GOSSYM is a physiologically detailed simulation model of the growth and the development of the cotton plant. It was developed at the Crop Simulation Research Unit (USDA-ARS) at the beginning of the 70's. The first model was named SIMCOT then it became GOSSYM with the integration of a soil model to the SIMCOT plant simulation.

COTONS is a materials balance model, that means that demand in carbohydrate equal supply of carbohydrate. Different processes are currently modeled at different levels:

- photosynthesis is modeled at the canopy level,
- topology and abscission are modeled at the organ level,
- demand is model at both levels

In COTONS there are two main submodels: a plant model and a soil model. The plant model is driven by weather information, cultural practices, and genetic characteristics. Plant development is limited by water and nitrogen supply and soil water potential status. When the plant grows it shade limits soil water evaporation but at the same time the plant uptakes and moves water and nitrogen.

From GOSSYM, the plant sub-model of COTONS includes two important concepts: materials balance" and the use of different stresses (N, H2O, C) to regulate plant growth. The model runs on a daily basis. Each day, the model first calculates carbohydrate supply based on external factors (light, temperature, water supply, etc), plant water status and leaf area. Second, the system calculates the carbohydrate demand for Growth, Respiration and plant Maintenance based again on external factors and plant status. Third, the system partitions the carbohydrate supply to the different organs based on their demand and priority levels. Fruit having the highest priority and storage the lowest.

<u>Production of carbohydrates.</u> COTONS uses canopy characteristics to estimate the proportion of light going through the canopy. Two parts of incident light are identified: the light transmitted directly to the ground which is a function of plant height, plant width and row spacing and the light transmitted to the ground through the canopy which is a function of genetic plant characteristics and of the Leaf Area Index. This light interception model incorporates Beer-Lamber's law to estimate the light intercepted by the canopy. The photosynthesis model takes into account the size of the canopy and its age. The sub-model of carbohydrate production allows the simulation of light competition for plants growing in parallel.

<u>Demand in carbohydrates.</u> The modeling of carbohydrate demand in COTONS is based on the idea (DeWitt) that "crops have a growth potential when there are no limiting factors such as availability of carbon, nitrogen or water". In a first stage, the model estimates potential growth for the different parts of the plant. This is done organ by organ (except for the root) according to the weight and/or area of each organ, its age, and the temperature. These potentials for growth are reduced according to the water status of the plant and the use of growth regulators. In a second step, COTONS uses the adjusted growth potentials to calculate

the demand (the sum of the potentials) for carbohydrate and compares it with supply, the sum of net photosynthesis per day, and the available pool of carbohydrate. The demand/supply ratio [0, 1],'representing carbon stress', is then used for adjustment of growth potentials by plant organ type.

Partitioning of Carbohydrate Supply. The partitioning process links the carbohydrate supply sub-model and the carbohydrate demand sub-model. During each daily time step the partitioning process which drives the yield components and storage, balances the whole system. This process needs information on the plant structure which is dependent on the morphogenesis sub-model. The plant morphogenesis routine simulates the emergence of organs and the development of these organs according to the temperature "experienced" by the plant part being considered in the daily time step interval. Stresses experienced by the plant modify that growth and development. However, these morphogenetic events (COTONS makes no distinction between plastochron and phyllochron) are not determined using sums of temperatures. They are estimated from the calculated age of each organ in relation to an age threshold. The temperature "experienced" is used in (usually) quadratic polynomial equations to determine the age thresholds at which the various organs should emerge or change. Nitrogen stress and vegetative stress combined are also used in the calculation of age thresholds. These stresses are calculated prior to the calculation of growth and development. There are two pathways (both are supported and can be invoked from the interface) in the morphogenesis model: the "plant average" path and the "plant population" path. In the plant average it is assumed that one "plant average" represents the crop. In this case the simulation process is deterministic and fruit production per position is the proportion of fruit present at this position in the field. In the "plant population" path, the model simulates 'n' plants growing in parallel with the same environmental condition. The population of plants represents the actual variability observed in commercial fields. This variability is the interaction of a plant phenotypic variability and a competition between plants linked to the phenotypic variability and differences in stand establishment.

Plant variability is modeled by adding stochasticity into the node initiation and abscission processes, and by modeling these two main processes as a queueing system. For example, the probability density function of the node appearance can be fitted with the reciprocal of the normal function. This function has the key feature of having the shape and right-skew of most biological distribution processes. During the simulation of the plant development, if it is time to initiate a new node, the system will select a random number and initiate a new node if the value of this random number is above a threshold. This is the same process for fruit abscission. The square abscission model follows an exponential distribution and for the boll abscission model, a more complex distribution function is used. Morphogenesis is modeled as a queueing system with three queues, the first one is the internode elongation, the second is square abscission and the third is for boll abscission. Queue disciplines are different: for internode elongation the discipline is "First In First Out", for abscission processes it is "Last In First Out".

The variability linked to plant competition is modeled by adding an emergence sub-model and by growing plants in parallel on an area basis. The emergence model is currently only a function of temperature. It partially takes into account soil humidity, planting depth and other characteristics because the model uses the emergence date indicated by the farmer as the median for emergence distribution. The emergence model is based on the normal reciprocal function. This function has only two parameters which are very well correlated to the temperature. As stated above, the light and photosynthesis sub-models allow plant competition for light because light interception is simulated at the plant level and the size of the plant is taken into account.

Morphology, geometry and visualization. The use of a crop model by producers is difficult. For example, even if the developers of GOSSYM clearly had the objective to provide a decision support system to farmers, it was designed by modelers with techniques adapted to modelers and not to farmers. Although GOSSYM was a very good research tool for modelers, it was not often used by other scientists. The main reason for this problem was the interface of the system. In crop models both data input and interpretation of the output of the system may seem too abstract or too cumbersome for users. Graphical tools now exists and are available on desktop computers. Thus, it is possible to visualize output as "Virtual Plants" resulting from the simulation and making the simulation more understandable to farmer and scientists. The integration of a visualization tool to COTONS was facilitated by the level of detail simulated by the model. This visualization is done using an Architectural engine which simulates the sizes of each organ (length, diameter and width), their spatial position, the shape of each organ, and displays all these information. Each day the plant model of COTONS simulates plant growth and development, it then it calls a "Plant Morphology" sub-model which simulates sizes of all organs. It then calls another routine to build the 3D plant architecture by positioning all the plant organs in 3D space. Finally, a routine display the results. The morphology sub-model calculates volume and area variables (length and diameter) from dry weights simulated by the plant model. The architectural routine builds the 3-dimensional plant architecture from organ lengths and diameters, the phyllotaxy angles, insertion angles and deviation angles. All these angles are fixed and they are assumed to be variety dependent. Each organ is placed, by an iterative process, in the 3D space relatively to its bearer. Also a shape made from polygons is associated to each organ. The size of the shape is controlled by the morphology sub-model.

Simulating the Cotton Crop with COTONS. To initialize and run COTONS the user needs three kinds of inputs: single point descriptors as soil hydrology characteristics, plant density, date of emergence and so on, the driving variables (temperature, solar radiation, rainfall and wind speed) and the cultural (agronomic practices or technical itineraries) practices. With this information the system is able to simulate the growth of the crop during the crop season. At the end of the simulation the system provides the following outputs: organs mass and number, plant topology, plant status indicators and the variables used. During the simulation the user can visualize the plant growth as shown in figure 2-8. Figure 2 shows the visualization at three different days for an average plant corresponding to a crop with high nitrogen fertilization and good water supply. The plant is well developed and the production is localized at the bottom. Figure 3 shows, for the same three different days, the same crop but with a medium nitrogen fertilization instead of a good nitrogen fertilization. The plant is smaller and the boll sizes are smaller. In figure 4 the conditions are: no nitrogen and a low water supply. This is typically a "top crop production" as often found in the Texas high plains, the plant stops its growth early in the season because of water and nitrogen stresses. The three final average plants are shown in figure 5. It is obvious that this kind of output is more accessible for users than a simple listing of tables (which are also available). Figure 6 shows 8 plants growing in parallel as they are simulated by the new system. All the plant are different, plant height, number of bolls, boll position, etc., are different. They did not emerge necessary the same day and they had to compete for light interception.

Conclusion. The new COTONS model integrates many features available only individually in other models. For the first time, a mechanistic model associates an architectural engine, a visualization tool and is able to simulate field variability using parallel population processes. COTONS' light interception and photosynthesis sub-models take into account plant and crop structures giving the foundation for a "plant population" model as an alternative to the common "average plant" model approach. With the inclusion of stochasticity and emergence process, COTONS is able to simulate field variability. It will allows management based on more indicators than other cotton models (weights, number of fruiting and vegetative branches, number of bolls by position, distribution of yield, etc.).
The visualization tool is really a Producer-Level Decision-Aid system. For example, the visualization of the effects of different management practices will demonstrate the results of alternative practices. COTONS, produces "life-like" plants and the farmer deals with simulation results analogous to the ones he dealt with in a 3-dimensional world. Now dry weights, nitrogen stress, water stress, etc, correspond to the daily reality of the farmer so he/she is able to understand and accept recommendations provided by the system. Finally Virtual Plants are an ideal training tool. COTONS can be used to teach farmers and students optimal cultural practices, sampling and monitoring techniques, and the overall complexity, interactions and feedback associated with agricultural production.

Key References

Baker, D., McKinion, J. M., and Lambert, J. R. (1983). "GOSSYM: a Simulator of Cotton Crop Growth and Yield.,". S.C. Agric. Exp. Stn.

Baulch, P. W., McCarter, K., Staggenborg, S., and Lambert, J. R. (1995). "GOSSYM-COMAX, User's Manual,". AGBIT, Inc., Starkville, MS.

de Reffye, P. (1979). Modélisation de l'architecture des arbres par des processus stochastistiques. Simulation spatiale des modèles tropicaux sous l'effet de la pesanteur. Application au *coffea robusta*, Paris-Sud, Orsay, France.

de Witt, C. T., and Brouwer, R. (1968). A Dynamic Model of the Vegetative Growth of Crops. *Das Zietschrift Fur Angewandte Botanik.*

Duncan, W. G., Loomis, R. S., Williams, W. A., and Hanau, R. (1967). A model for Simulating Photosynthesis in Plant Communities. *Hilgardia, Journal of agriculture and Science* **38**, 181-205.

Gutierrez, A. P., Falcon, L. A., Loew, W., Leipzig, P. A., and Van Der Bosch, R. (1975). An Analysis of Cotton Production in California: A Model for Acal Cotton and the Effects of Defoliators on Its Yields. *Environmental Entomology* **4**, 125-136.

Jackson, B. S., Arkin, G. F., and Hearn, A. B. (1988a). "COTTAM: A Cotton Plant Simulation Model for an IBM PC Microcomputer," Rep. No. 1/88. TAES, Temple, Texas.

Jallas, E. (1991). Modélisation de Développement et de la Croissance du Cotonnier. Mémoire de DEA, INA-PG, Paris.

Jallas, E. (1998). Improved Model-Based Decision Support by Modeling Cotton Variability and Using Evolutionary Algorithms. PhD Dissertation, M.S.U., Mississippi.

Jones, C. A., and Kiniry, J. R., eds. (1986). "CERES-Maize. A simulation Model of Maize Growth and Development,", pp.. 1-194. Texas A&M University Press, College Station.

McKinion, J. M., Baker, D. N., Whisler, F. D., and Lambert, J. R. (1989). Application of the GOSSYM/COMAX System to Cotton Crop Management. *Agricultural Systems* **31**, 55-65.

Mutsaers, H. J. W. (1984). KUTUN: a Morphogenetic Model for Cotton. *Agricultural Systems* **14**, 229-257.

Sequeira, R. A., Sharpe, P. J. H., Stone, N. D., El-Zik, K. M., and Makela, M. E. (1991). Object-oriented Simulation: Plant Growth and Discrete Organ to Organ Interactions. *Ecological Modelling* **58**, 55-89.

Sequeira, R. A., Stone, N. D., Makela, M. E., El-Zik, K. M., and Sharpe, P. J. H. (1993). Generation of Mechanistic Variability in a Process-based Object-oriented Plant Model. *Ecological Modelling* **67**, 285-306.

Sequeira, R. A., and Jallas, E. (1995). The Simulation Model GOSSYM and its Decision Support System, COMAX: its Applications in American Agriculture. *Agriculture et Developpement* **8**, 25-34.

Thanisawanyangkura, S., Sinoquet, H., Rivet, P., Crétenet, M., and Jallas, E. (1997). Leaf Orientation and Sunlit Leaf Area Distribution in Cotton. *Agricultural and Forest Meteorology* **86**, 1-15.

Wallach, D. (1978). A Simple Model of Cotton Yield Development. *Field Crops Research* **1**, 269-281.

Baker, D., McKinion, J. M., and Lambert, J. R. (1983). "GOSSYM: a Simulator of Cotton Crop Growth and Yield.,". S.C. Agric. Exp. Stn.

Baulch, P. W., McCarter, K., Staggenborg, S., and Lambert, J. R. (1995). "GOSSYM-COMAX, User's Manual,". AGBIT, Inc., Starkville, MS.

de Reffye, P. (1979). Modélisation de l'architecture des arbres par des processus stochastistiques. Simulation spatiale des modèles tropicaux sous l'effet de la pesanteur. Application au *coffea robusta*, Paris-Sud, Orsay, France.

de Witt, C. T., and Brouwer, R. (1968). A Dynamic Model of the Vegetative Growth of Crops. *Das Zietschrift Fur Angewandte Botanik.*

Duncan, W. G., Loomis, R. S., Williams, W. A., and Hanau, R. (1967). A model for Simulating Photosynthesis in Plant Communities. *Hilgardia, Journal of agriculture and Science* **38**, 181-205.

Gutierrez, A. P., Falcon, L. A., Loew, W., Leipzig, P. A., and Van Der Bosch, R. (1975). An Analysis of Cotton Production in California: A Model for Acal Cotton and the Effects of Defoliators on Its Yields. *Environmental Entomology* **4**, 125-136.

Jackson, B. S., Arkin, G. F., and Hearn, A. B. (1988a). "COTTAM: A Cotton Plant Simulation Model for an IBM PC Microcomputer," Rep. No. 1/88. TAES, Temple, Texas.

Jallas, E. (1991). Modélisation de Développement et de la Croissance du Cotonnier. Mémoire de DEA, INA-PG, Paris.

Jallas, E. (1998). Improved Model-Based Decision Support by Modeling Cotton Variability and Using Evolutionary Algorithms. PhD Dissertation, M.S.U., Mississippi.

Jones, C. A., and Kiniry, J. R., eds. (1986). "CERES-Maize. A simulation Model of Maize Growth and Development,", pp.. 1-194. Texas A&M University Press, College Station.

McKinion, J. M., Baker, D. N., Whisler, F. D., and Lambert, J. R. (1989). Application of the GOSSYM/COMAX System to Cotton Crop Management. *Agricultural Systems* **31**, 55-65.

Mutsaers, H. J. W. (1984). KUTUN: a Morphogenetic Model for Cotton. *Agricultural Systems* **14**, 229-257.

Sequeira, R. A., Sharpe, P. J. H., Stone, N. D., El-Zik, K. M., and Makela, M. E. (1991). Object-oriented Simulation: Plant Growth and Discrete Organ to Organ Interactions. *Ecological Modelling* **58**, 55-89.

Sequeira, R. A., Stone, N. D., Makela, M. E., El-Zik, K. M., and Sharpe, P. J. H. (1993). Generation of Mechanistic Variability in a Process-based Object-oriented Plant Model. *Ecological Modelling* **67**, 285-306.

Sequeira, R. A., and Jallas, E. (1995). The Simulation Model GOSSYM and its Decision Support System, COMAX: its Applications in American Agriculture. *Agriculture et Developpement* **8**, 25-34.

Thanisawanyangkura, S., Sinoquet, H., Rivet, P., Crétenet, M., and Jallas, E. (1997). Leaf Orientation and Sunlit Leaf Area Distribution in Cotton. *Agricultural and Forest Meteorology* **86**, 1-15.

Wallach, D. (1978). A Simple Model of Cotton Yield Development. *Field Crops Research* **1**, 269-281.

Figures

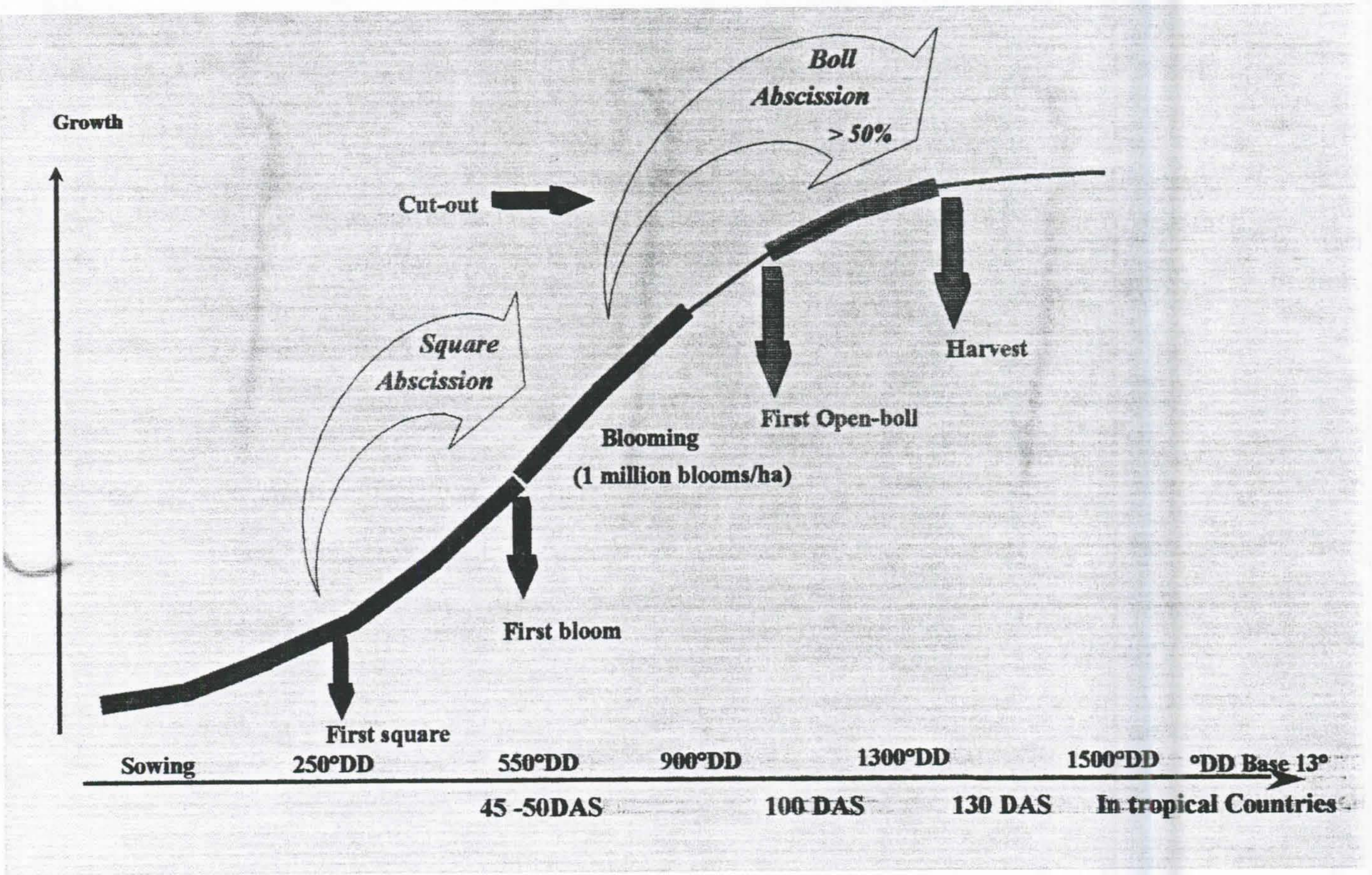

Figure 1: Cotton Growth.

Figure 2: Visualization at three different days of a plant average for a crop with high nitrogen fertilization and good water supply.

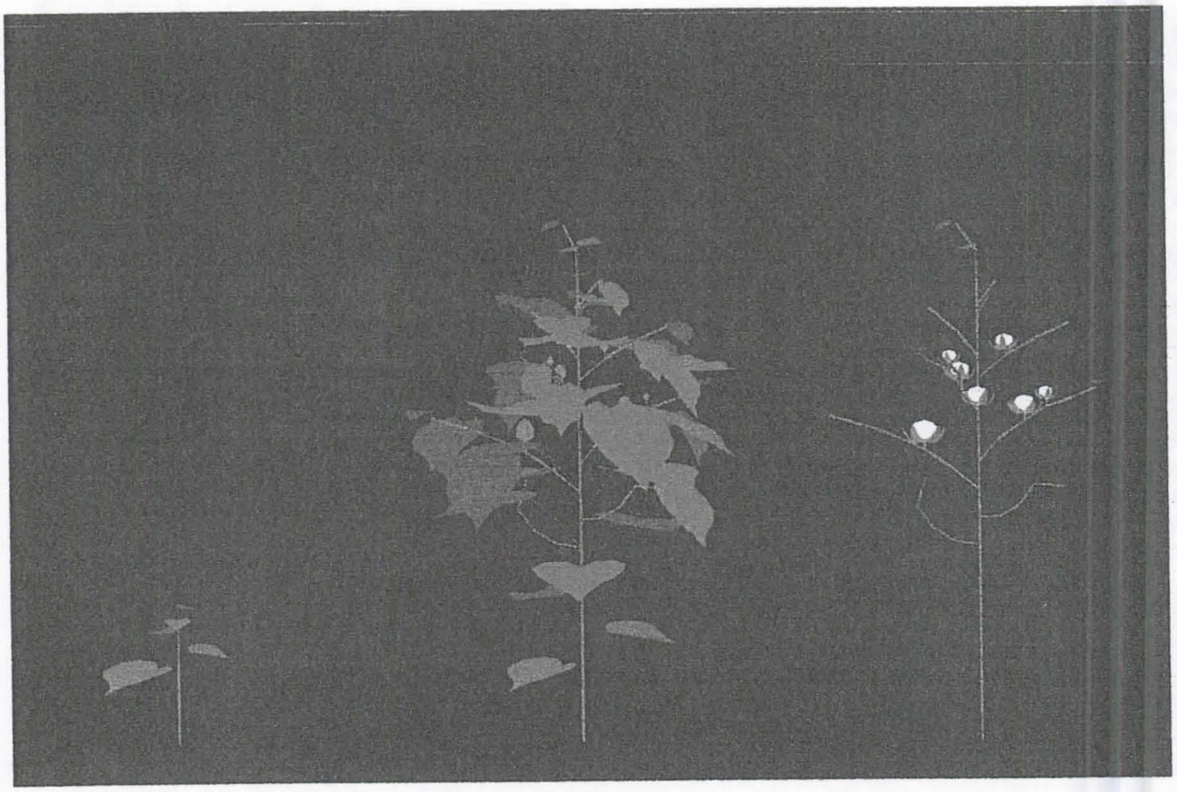

Figure 3: Visualization at three different days of a plant average for a crop with low nitrogen fertilization and good water supply.

Figure 4: Visualization at three different days of a plant average for a crop with no nitrogen fertilization and low water supply

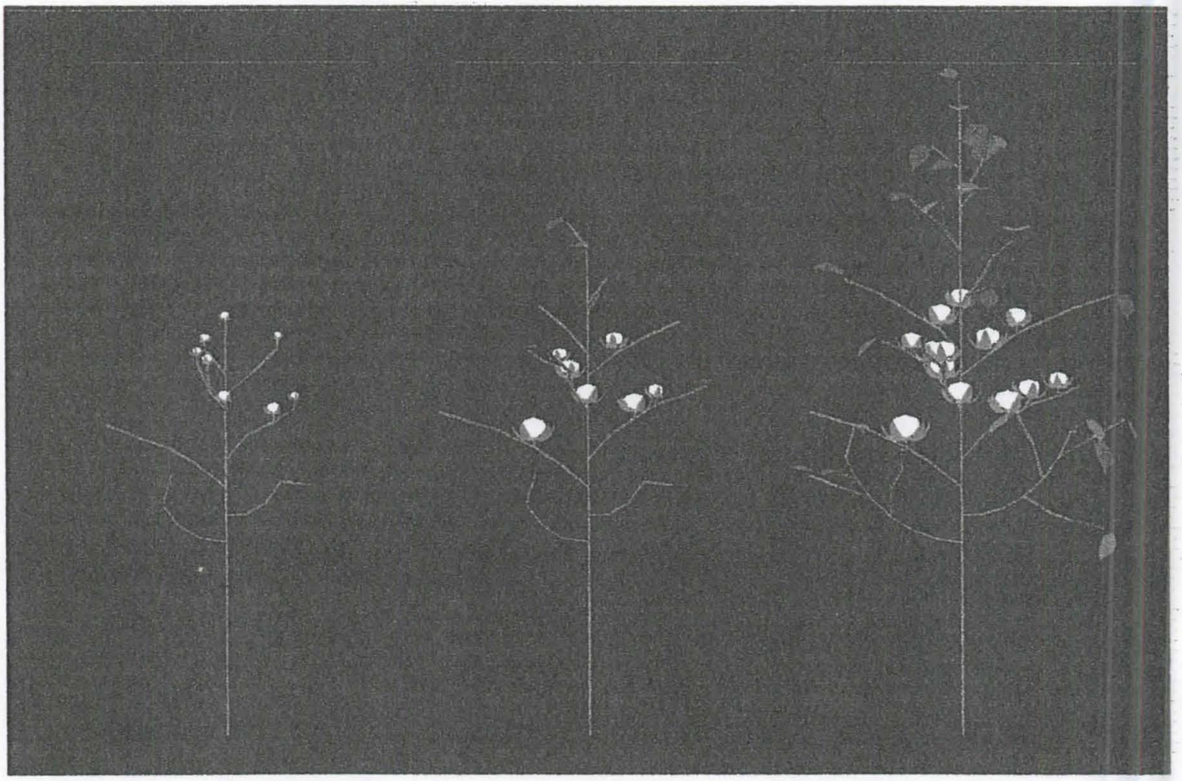

Figure 5: Visualization of the three different plant average at their final stage. Left plant represents a crop with no nitrogen and low water supply, middle plant represents a crop with low nitrogen supply but a good water supply and plant on the right represents a crop with optimal cultural inputs.

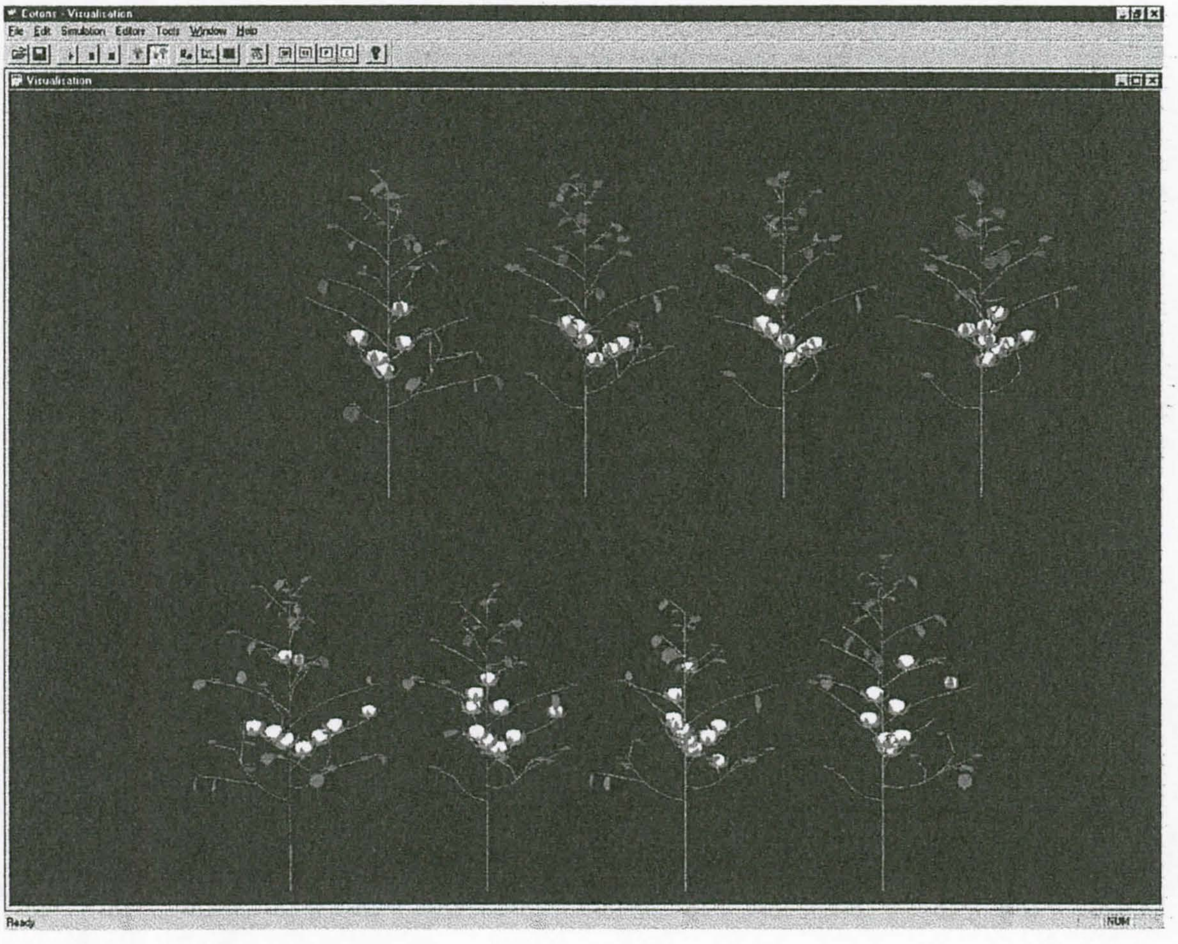

Figure 6: Visualization of 8 plants growing in parallel